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STRONG INTERACTIONS IN THE 25-FT BUBBLE CHAMBER

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Introduction

It has already been pointed out by Snow[1] and others that the proposed 25-ft bubble chamber will be quite essential to a neutrino program appropriately matched to the capabilities of the NAL accelerator. Since typical neutrino energies are of the order of 10 BeV, the analysis problems are perhaps not too much greater than those already encountered in the conventional ~1 m^3 bubble chambers in strongly interacting particle beams in this energy range. The rate problem in neutrino physics suggests a chamber in the ~100 m^3 range, and once this volume is achieved, there seems little doubt that the event analysis will be feasible.

The strong-interaction problem appears in a different light. On the one hand the extrapolation of present bubble-chamber analysis techniques to very high energies poses serious problems, whereas, on the other hand, the development of counter and spark-chamber techniques provides alternative and perhaps more attractive ways of doing at least some strong-interaction experiments. Nevertheless, the purpose of this note is to express and justify the view that within a limited context, a chamber such as the one described in the BNL proposal has a serious role to play in strong interactions at high energy.

In taking this position, we do not wish in anyway to refute the argument that given a specific problem one can design a spark chamber setup which can solve the problem with more precision, better statistics and less cost than the construction cost of the bubble chamber. However, the multiplicity of all such possible strong-interaction experiments is very large, and some exploration as to which experiments are interesting and which are likely to answer useful questions will be essential. It seems to us that the role of the bubble chamber will be to explore inelastic processes over a certain useful energy range, to obtain in some cases definitive results and in other cases raise questions where solutions by means of appropriate spark-chamber experiments will lead to real progress.

Having defined such a role, one must now look in more detail to see if there is indeed a useful energy region over which the bubble chamber can be used in the reconstruction of a sufficiently large range of types of inelastic events to represent a useful technique. In the considerations which follow, it will be argued that at least up to primary energies of about 60 BeV, events with none or one missing neutral will be analyzable by the proposed chamber in the sense that a complete kinematic reconstruction of a large fraction of the events will be possible. Is this a useful energy range, even though it does not completely encompass the capabilities of the accelerator? In fact, it presently seems unlikely that inelastic processes of energy above 15 BeV will have been extensively studied by the time that the NAL accelerator turns on. In the United States, the only bubble chamber really matched to such energies is the ANL 12-ft chamber which, however, will be otherwise occupied until the startup at Weston. In Europe, the CERN 3.5-m chamber and the Mirabelle chamber at Serpukhov will be reasonably matched to beams of this energy, but since these chambers will not be in full production for several years, it still appears likely that the energy region above 15 BeV will not have been extensively studied by the time of the Weston startup. Thus, at the very least, it appears that the energy domain between 15 and 60 BeV can be very usefully studied by the proposed 25-ft chamber.

4c Fits

We now consider in some detail the analysis of an event at a primary energy of 60 BeV. In considering the errors, we have made precisely the same assumptions as those discussed in the report by Kraemer and Derrick.[2] In particular, we have used their error formulas (1) and (2), which we repeat here

$$\left(\frac{\Delta p}{p}\right)^2 = \frac{0.133\alpha}{H^2 \ell} + \frac{1.44 \times 10^{-4} p^2 \epsilon^2}{H^2 \ell^5}, \tag{1}$$

$$(\Delta\theta)^2 = \frac{2 \times 10^{-3} \alpha \ell}{p^2} + \frac{3.8 \times 10^{-6} \epsilon^2}{\ell^3} \tag{2}$$

where H = kG

p = MeV/c

ϵ = microns in space taken to be 500

ℓ = length in cm

θ = azimuth angle in radians

α = 20.

We consider explicitly a six-prong interaction produced by a 60-BeV incident particle. To make a specific calculation, we consider two possible models:

(i) the outgoing prongs share the incident energy equally.

(ii) one outgoing prong carries 80% of the incident energy, the other 20% being divided up equally among the other fine prongs.

We address ourselves first to the following question: How well can we know that there is no outgoing neutral particle? The question of direct detection of outgoing neutrals, such as gamma-ray detection, will be considered further on; and for the moment, we consider only information based on momentum and angular measurements of the visible prongs. We also assume that by appropriate beam design, uncertainties in the incident particle momentum and direction are negligible in comparison to measurement errors of the secondaries. We now consider each of the above models in turn.

(i) All six outgoing prongs share the incident energy equally. First of all, to eliminate difficulties due to secondary interactions, we require that all track lengths be greater than 1.2 m, a condition fulfilled by 50% of all six-prong interactions if we take the interaction length to be 11 m. We then calculate $\Delta p/p$ from formula (1) as follows. If we rewrite (1) in the schematic form

$$\left(\frac{\Delta p}{p}\right)^2 = \frac{A}{\ell} + \frac{Bp^2}{\ell^5}, \tag{3}$$

we then average $(\Delta p/p)^2$ over all lengths between the minimum length $\ell_{min} = 1.2$ m as given above and the maximum length ℓ_{max} determined by the bubble-chamber size, using as weighting factor the probability of a given length ℓ,

$$\mathrm{Prob}\,(\ell)\,d\ell = \frac{d\ell}{\lambda}\left(\frac{1}{1-\frac{\ell_{min}}{\lambda}}\right) \qquad \ell_{min} \leq \ell \leq \ell_{max},$$

$$\mathrm{Prob}\left(\ell = \ell_{max}\right) = \left(1 - \frac{\ell_{max}}{\lambda}\right) \Bigg/ \left(1 - \frac{\ell_{min}}{\lambda}\right), \tag{4}$$

where λ is the interaction length assumed $>> \ell$. Thus, the average $(\Delta p/p)^2$ is given by

$$\left(\frac{\Delta p}{p}\right)^2_{av} = \int_{\ell_{min}}^{\ell_{max}} \left(\frac{\Delta p}{p}\right)^2 \Bigg|_{\ell} \mathrm{Prob}\,(\ell)\,d\ell + \mathrm{Prob}\,(\ell = \ell_{max})\left(\frac{\Delta p}{p}\right)^2 \Bigg|_{\ell_{max}}$$

$$\left(\frac{\Delta p}{p}\right)^2_{av} = \frac{\frac{A}{\lambda}\,\ell n\,\frac{\ell_{max}}{\ell_{min}} + \frac{Bp^2}{4\lambda}\left(\frac{1}{\ell_{min}^4} - \frac{1}{\ell_{max}^4}\right) + \left(1 - \frac{\ell_{max}}{\lambda}\right)\left(\frac{A}{\ell_{max}} + \frac{Bp^2}{\ell_{max}^5}\right)}{\left(1 - \frac{\ell_{min}}{\lambda}\right)} \tag{5}$$

where A and B are defined in Eq. (3).

We are also interested in the transverse momentum error

$$\left[\Delta(p\theta)\right]^2 = p^2(\Delta\theta)^2 + \theta^2(\Delta p)^2$$

$$= p^2(\Delta\theta)^2 + p_t^{\,2}\left(\frac{\Delta p}{p}\right)^2, \qquad (6)$$

where p_t is the transverse momentum taken to be typically 500 MeV/c in the ensuing calculations. To calculate the angular error, we note first that because $(\Delta\theta)^2$ in Eq. (2) has a minimum at a value of ℓ which is comparable with typical track lengths, it is actually insensitive to the value of ℓ, and we simply use a conservative average value of 2 m.

The results of the calculations for a value of ℓ_{max} = 3 m are as follows: For each track

$$\Delta p/p = 3 \times 10^{-3}; \qquad \Delta p = 3 \times 10^{-3} \times 10\ \text{BeV/c} = 30\ \text{MeV/c},$$

since each of the six prongs carries 10 BeV/c according to our model, and

$$\Delta\theta = 0.44\ \text{mrad},$$

$$\Delta(p\theta) = 4.4\ \text{MeV/c}.$$

Taking independent errors for the six tracks, the error in overall longitudinal momentum balance is $30 \times \sqrt{6} = 73$ MeV/c and in transverse momentum balance $4.4 \times \sqrt{6} = 11$ MeV/c. These two numbers are to be compared with typical momenta of a missing neutral, namely 10 BeV/c longitudinal and 500 MeV/c transverse. It appears rather clear that there will be no difficulty in deciding on the presence or absence of a missing neutral.

(ii) We now consider the second model in which one outgoing prong carries 80% of the incident momentum and the others divide the remaining momentum equally. In our case, the fast prong has a momentum of 48 BeV/c, and each of the other prongs carries 2.4 BeV/c. To insure measurability, we demand that the fast track have the full available track length of 3 m. Simple calculation shows that with a loss of no more than 50% of the events all other secondaries have measurable lengths of at least 73 cm prior to making any secondary interactions. As will be seen shortly, this length, short as it may seem, is adequate to reduce the slow-particle error contributions to a negligible level!

Application of Eqs. (1), (2), and (6) (with $\ell = 3$ m) to the fast prong and Eq. (5) (with $\ell_{min} = 0.73$ m, $\ell_{max} = 3$ m) to the slow prongs leads to the following results:

$$\left(\frac{\Delta p}{p}\right)_{fast} = 5 \times 10^{-3} \qquad (\Delta p)_{fast} = 240 \text{ MeV/c}$$

$$(\Delta p\theta)_{fast} = 9.6 \text{ MeV/c}$$

$$\left(\frac{\Delta p}{p}\right)_{slow} = 2.7 \times 10^{-3} \qquad (\Delta p)_{slow} = 6 \text{ MeV/c}$$

$$(\Delta p\theta)_{slow} = 3 \text{ MeV/c} .$$

Again, combining the fast and slow prongs we obtain as the overall errors in longitudinal and transverse momentum unbalance

$$\Delta p = 240 \text{ MeV/c},$$

$$\Delta(p\,\theta) = 12 \text{ MeV/c}.$$

These values, although larger than the ones obtained in model (i) are still very small in comparison to the momenta taken up by a missing particle.

We conclude from these calculations that there appears to be no problem in separating events without a missing neutral from those with missing neutrals at least up to incident energies of 60 BeV. It seems likely that this result applies to even somewhat higher energies, although for outgoing particles which carry higher momentum than the ones considered here the errors rise rapidly with momentum. It spite of secondary interactions of outgoing prongs, there appears to be very adequate precision with selection criteria which do not throw away more than 50% of the events.

Finally, it is worth mentioning the problem of identifying the secondary prongs. It has been shown by Trilling[3] that for 4c events the constraints of momentum conservation lead to a situation where the kinematic discrimination between various mass assignments is as good at high momentum as at low momentum provided that the beam energy is well defined. Furthermore, the magnetic trapping and secondary interaction effects will provide additional information not usually available in present bubble chambers.

One remark concerning the data-handling problem for 4c events is perhaps worthwhile here. It may appear that if one wants to handle 4c events at high energy, one has the enormous task of measuring a huge number of unfittable events with many π^o in order to get a few 4c interactions. As will be shown a little further, with a 3-m potential length the conversion probability for a gamma ray in the hydrogen is 25%. Thus, for a 1 π^o event there is a 44% probability of detecting at least one gamma and for a 2 π^o event there is a 68% probability of detecting one or more gammas. Consequently, if one wanted to handle only 4c events, one could construct scanning criteria which eliminated many of the background events before measurement.

<u>1c Fits</u>

Suppose that we have an event in which momentum balance fails, implying the presence of an unknown neutral particle. What can we say about the use of energy and momentum balance considerations to identify the particle?

The formulas for evaluating missing mass errors are given in the report of Fields et al.[4] Without going into great numerical detail, if we substitute the errors in p and $(p\theta)$ calculated in the previous section into the formulas we obtain typical values of error in $(MM)^2$ of about 0.04 $(BeV)^2$ arising equally from the error in p and the error in $(p\theta)$. It is interesting to note that though the error in longitudinal momentum is about 20 times that in transverse momentum, the missing mass is so much more sensitive to the transverse momentum that the two error contributions are about equal.

The above error limits are adequate to distinguish between a missing neutron and a missing neutron plus neutral pions but not adequate to distinguish between one and more than one missing neutral pion. Moreover, there is a further very powerful handle available with a large chamber. Suppose that the average available path length is about 3 m (half of the 25-ft chamber). The gamma-ray conversion probability is 25% in the hydrogen, and in 44% of all one-missing π^o events one gamma ray is converted in hydrogen. The energy and direction of the converted photon add another constraint making the event a 2c fit. It is easily shown that this additional constraint is a meaningful one provided that the gamma energy measurement is reasonably accurate (a few percent) and provided that the "missing" transverse momentum taken up by the π^o is known to a fraction of a pion mass. As pointed out in the previous section, this transverse momentum for a 60 BeV primary is, in fact, known to about ±12 MeV/c which is indeed much smaller than a pion mass. The gamma momentum measurement will be accurate to about 3% which is also adequate.

It thus appears, that with reasonable probability (~ 40%) one can handle events with one missing neutral pion without too much difficulty. The problem of identifying the secondary prongs by kinematics is difficult to consider except by detailed Monte Carlo studies. In any case, just as for the 4c events, the trapping and secondary interactions should help in the identification.

12-Ft vs 25-Ft Chamber for Strong Interactions

Most of the considerations given so far apply to the 25-ft chamber insofar as a magnetic field of 40 kG, and a potential path length of 3 m are useful to provide good measuring precision and reasonable gamma conversion probability for 1 π^o events. The 12-ft chamber actually has a 3.9-m diameter. Thus, if we take a fiducial volume restricted to the upstream half of the chamber, we will obtain an average path length of about 3 m. The present field of only 20 kG for the 12-ft chamber would somewhat reduce the precision. It would appear on first look that the two million dollars estimated to boost the field of the 12-ft chamber to 40 kG would be well spent, at least insofar as the analysis of strong interactions is concerned. With this modification, the 12-ft chamber is not compellingly less useful than the 25-ft in strong-interaction physics.

Conclusion

We conclude from the foregoing analysis that either the 12-ft or the proposed 25-ft chamber, with fairly realistic error assumptions and a 40-kG field, can be used to obtain completely analyzed events, either with no neutrals or with one missing neutron, π^o for incident beam energies at least as high as 60 BeV. While the study of a particular well-defined reaction may be more effectively done by a triggered system, the large chamber still appears to remain useful as a general survey instrument in the study of strong interactions.

REFERENCES

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[3] G. Trilling, SLAC Summer Study Report 5-E, 1962.

[4] T. Fields et al., NAL Summer Study Report A. 3-68-12, 1968.